

THE INFLUENCE OF SUPPLY NETWORK STRUCTURE ON FIRM INNOVATION PERFORMANCE

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ABSTRACT

In this study, we examine the structural characteristics of supply chains as networks and investigate how supply network structure impacts firm innovation. Specifically, we investigate the relationship between three supply network characteristics (supply network interconnectedness, supply network accessibility, and supply network partner innovativeness) and a firm's innovation output. Our findings suggest direct benefits arising from supply network accessibility and partner innovativeness towards a firm's innovation output. The findings also highlight that firms that are part of interconnected supply networks can enhance their innovation output. This study contributes to the stream of research recognizing supply networks as a source of innovation.

Keywords: innovation, supply networks, social network analysis, supply chain management

INTRODUCTION

Supply chains as complex networked systems comprise not only a firm's direct ties to respective firms (e.g. suppliers and customers), but also its indirect ties to the supplier and customer base of these respective firms. Hence, supply chains are often regarded as *supply networks* with several interacting and inter-dependent firms [1]. Traditional dyadic approaches such as buyer-supplier or supplier-supplier assessments interpret the value of each supply network relationship in isolation. This approach excludes several benefits or vulnerabilities arising from a supplier's extended network when considering performance implications of selecting a particular supplier

[2]. Thus, effective design and management of innovative supply networks requires consideration that moves beyond traditional dyadic (and more recently triadic) approaches.

A firm's level of innovative output is a by-product of its knowledge creation activities and often results in inventions that reflect advancements over existing technology. Previous research has emphasized the benefits of adopting a network perspective when considering innovation and performance implications in operations and supply chain research [3, 4, 5]. Borgatti and Li [6] provide an initial overview of SNA and its potential network mechanisms and characteristics that can be implemented by SCM researchers. Also, Bellamy and Basole [7] provide a systematic review and synthesis of network analysis studies in the supply chain literature. Supply networks have been recognized as a locus of innovation, with firms relying less on internal capabilities for innovative output and instead tapping into the knowledge of their suppliers and customers [8, 9]. For example, Toyota was able to foster a series of network-wide knowledge-sharing processes among their supplier and customer base by establishing a series of highly interconnected supplier sub-networks. The creation of these sub-networks and further investments in subsidizing network activities allowed Toyota to experience greater inflow of both explicit and tacit knowledge [8]. Examples such as this shed light on the possibility for firms to cultivate supply networks that lead to greater innovation output because of superior knowledge-sharing routines among their suppliers [9].

Several scholars have made attempts at understanding the underlying mechanisms in relationships and networks that enable a firm to be more innovative and develop new technologies, products and processes [10]. Autry and Griffis [5] develop certain propositions focused on the impact of supply network structure on firm innovation. Anchoring their ideas in both social capital and social network theory, these authors conjecture that the way a firm's supply network is structured and the strength of its ties impacts its ability to leverage new or specialized ideas, methods, or advancements [5]. The authors end by suggesting future research to empirically examine and test such proposals.

Despite the looming interest of supply networks in operations and supply chain research, few studies have empirically examined structural characteristics of supply networks in terms of the supply-based and/or alliance-based relationships. The few empirical-based studies in this domain include the examination of the automotive industry [11, 12, 13] and logistics projects [14]. Moreover, to our knowledge, prior studies have not examined the structural characteristics based on the series of supplier and customer relationships in high-technology environments that require high levels of innovative output from a firm for growth.

Our study helps address this gap in extant literature by incorporating the structural characteristics within supply networks when considering firm innovation. This study seeks to address the following research question: *What impact does the structure of a firm's supply network have on its innovative output?* Specifically, we examine two structural characteristics; *supply network interconnectedness* – the extent to which a firm's supply network partners are densely interconnected – and *supply network reachability* – corresponding to the speed and likelihood of information access between a firm and its supply network. We also factor in *supply network partner innovativeness* – an innovation-based characteristic of a firm's supply network partners – and its impact on innovation output. We incorporate the structural characteristics into our model

using data from multiple sources that document supplier and customer relationships. Also, we incorporate innovation-based characteristics into our model using the patenting activity of firms within the global electronics industry.

This work contributes to supply chain management research in several ways. First, it highlights the role of the supply network structure in driving a firm's innovative output thereby improving upon research on social capital and dyadic buyer–supplier relations [15, 16] and innovation implications by incorporating the broader effects of the overall supply network. Our work could serve as a building block in validating the argument that the that most firms do not innovate in isolation, but instead derive a significant amount of innovation from compendium of supplier and customer interactions beyond their linear, dyadic relations [17]. Second, it is recognized that innovation is a fundamental determinant of a firm's long-term survival [18] and this study contributes by verifying that suppliers have become an increasingly significant source of a particular firm's innovative output. Specifically, this work empirically shows that firms who experience a higher level of innovative output from their supply network are those with (1) densely connected networks of supply and alliance relationships that facilitate collaboration and knowledge transfer among partners and (2) supply and alliance relationships that increase the speed and likelihood of information access from a wide variety of firms. Lastly, as a result of our findings, we offer promising research avenues for research on supply networks and innovation in the operations and supply chain domain.

The remainder of this study proceeds as follows. In Section 2, we discuss the literature on innovation, supply chain management, and networks and develop hypotheses relating these structural characteristics to firm innovative output. We describe our research methodology in Section 3 and our empirical analysis and results in Section 4. We end in Section 5 by discussing our research findings, implications for theory and practitioners, and future research opportunities.

THEORETICAL BACKGROUND AND HYPOTHESES DEVELOPMENT

Innovation

Firm innovation acts as an enabler to develop unique products and services that help a firm gain competitive advantage in two ways. First, innovation spurs the creation of new knowledge and is often spawned from a novel recombination of existing knowledge, problems, or solutions [19]. The organizational learning literature distinguishes between the types of innovation based on the degree of new knowledge embedded in an innovation, resulting in a continuum of innovations that range from incremental to radical [20]. Incremental innovations emphasize the development of existing resources, knowledge, or abilities and are regarded as containing a low degree of new knowledge. Conversely, radical innovations emphasize the search and discovery of new resources, knowledge, or abilities and are regarded as containing a high degree of new knowledge [20, 21]. Second, in terms of operations-based performance metrics, supplier innovativeness has also been positively linked to manufacturer cost improvement, quality, product development, flexibility, and delivery speed [22]. Additionally, innovative activities of suppliers—such as value analysis and value engineering—have been shown to maintain operational functionality while reducing cost [23]. Lastly, scholars have demonstrated that higher firm innovativeness has been linked to greater firm profit [24, 25].

Researchers in knowledge management have explained that certain firms thrive from knowledge acquisition during the innovation discovery stage by learning in part from interactions with suppliers and customers [26]. The knowledge acquired from these interactions serves a key driver of the entrepreneurial capabilities that impact the quality and quantity of opportunities and innovations discovered by a firm [27]. The benefits derived from knowledge transfer between external sources have been shown to extend to an organizations' ability to assess the value of ensuing innovation opportunities in ambiguous environments [28, 29]. An organization can mitigate some of the environmental ambiguity by engaging in vicarious learning [30]—where organizations acquire second-hand knowledge and experience from other organizations—for feedback about the true nature of the environment that they face. Over the past decades, numerous studies have recognized a firm's network of suppliers and customers as a potential port of timely access to knowledge and resources [31]. Theories grounded primarily in social capital theory, supply networks, and supply chain collaboration help explain firm benefits derived by leveraging resources and knowledge from the network of available suppliers and customers.

Supply Networks as Conduits Of Knowledge, Resource, and Information Flow

Literature on social capital theory emphasizes that the assets emanating from access to knowledge, resources, and information available within a network of relationships can help explain the value that lies within a firm's supply chain. A core principle of this theory is the notion that firms involved in an exchange are embedded within the larger network of relationships, comprising other firms who are able to provide access to unique resources, information, and influence [32]. One argument manifesting from this perspective is that when firms are modeled to behave with perfect economic rationality, they ignore external social forces as critical sources shaping and constraining firm behavior. Adhering to this rationale, firms may gain comparable performance advantages through their level of embeddedness within the supply network in which they operate [5]. A firm's social capital helps facilitate the knowledge creation process by affecting the conditions necessary for exchange and combination to occur [33].

Nahapiet and Ghoshal [33] describe social capital across three dimensions: structural, cognitive, and relational capital. The structural dimension of social capital refers to the overall pattern of connections between partnering firms, mapping who a particular firm reaches and how they reach them. From this dimension, the network structure derived from a firm's compendium of ties determine, in part, opportunities and constraints to access valuable resources and information that would help them sustain a competitive advantage [34]. Several studies have underlined the benefits of structural capital as derived from the network characteristics and a firm's position in the network [e.g. 26, 35, 36]. The cognitive dimension refers to those resources that help generate shared language and vocabulary and the sharing of collective narratives [33]. Higher levels of cognitive social capital are thus derived from the collective goals and aspirations between partners, and can help stifle opportunistic behavior and conflicts as well as maximize the joint returns for both parties [15]. Lastly, the relational dimension of social capital refers to the degree of mutual respect, trust, and close interaction that exists between a firm and its partners [37, 38]. From a relational view, firms can profit from collaborative efforts with other partnering firms by creating joint benefits that would have not been possible to create by either firm in isolation [39]. Partnering firms can increase their level of relational capital by combining

and exchanging unique resources, knowledge, and abilities through relation-specific investments, knowledge sharing opportunities, and complementary resource endowments [40].

Several studies in supply chain management have shown how an increase in a focal firm's social capital can lead to an increase in operational and strategic performance [e.g. 41, 42, 43]. There are, however, important research gaps in the literature using social capital in the supply chain context that will benefit from further examination. First, little is known on the implications of social capital derived by a firm from its supply network on its innovative output. Second, prior studies on social capital gains focus on the traditional perspective of dyadic relations (e.g. buyer-supplier, supplier-supplier), thus ignoring the effects from firms being embedded within a larger context of the supply network as a whole [2, 3]. For example, a buyer and supplier operating in a densely connected supply network have greater opportunity to forgo heavy internal investments in social capital; instead, they can leverage more social capital externally from other partners in the supply network [44]. Thus, by not factoring in a supplier's extended network, a buyer has a limited understanding of these external social capital gains. This is a limitation that cannot be addressed by analyzing dyadic buyer-supplier relations in isolation [15].

Supply Networks and Firm-Level Innovation

Recent studies have extended the conventional view of innovations in context of supply chain management. For example, knowledge creation and innovation generation is derived not solely from a buyer but also from series of technical interactions that take place between the buyer and its suppliers [See 45]. These studies conceptually argue that the majority of firms will experience greater innovative output by engaging in innovation-related collaborations [46]. Support for this argument is found in Pittaway et al.'s [17] recent review of papers linking the networking behavior of firms with their innovative output. This review demonstrated the relevance of supply networks and the value of supplier interactions within the innovation process. These interactions are derived from two fundamental types of relationships in a supply network: supply agreements and alliance agreements [47]. Supply agreements typically involve contractual agreements between a buyer and supplier involving the provision of a good or service. Alliance agreements typically involve some sort of collaboration or transfer of knowledge or information that leads to mutual benefits between both parties. Some examples are joint product development agreements, joint ventures, and technology exchanges [48]. While several studies in the organizational science and strategy domains have quantified the structural characteristics of strategic alliance networks and their impact on firm innovation [e.g. 49, 50], these findings have not yet been well analyzed and translated into the operations and supply chain management domains.

In an effort to contribute to research on innovation within supply networks, we highlight two structural characteristics that arise from the supply and alliance relationships within the supply network and their impact on innovation: (1) *Supply network interconnectedness* and (2) *Supply network reachability*. We also incorporate effects of the level of innovativeness of a firm's supply network partners (*supply network partner innovativeness*). These relationships are illustrated in Fig. 1.

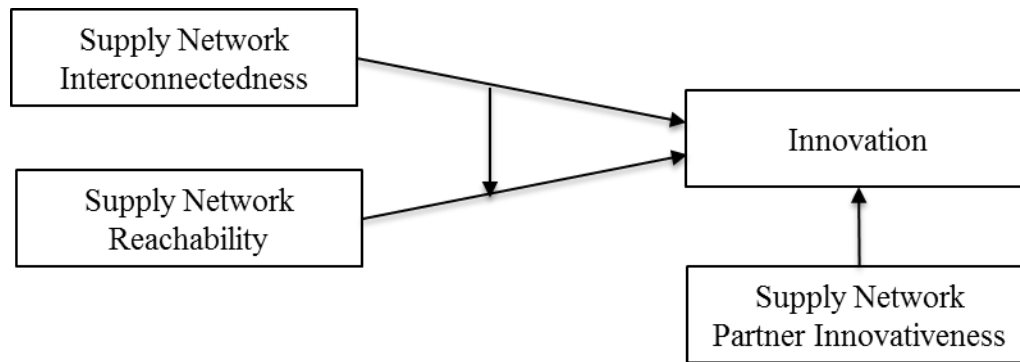


FIGURE 1.
Conceptual Model

Supply Network Interconnectedness

The strategic forming of collaborative supply chain environments, as facilitators of innovation, has generated a great deal of interest that has led to a new perspective of supply chain management and industry structure [51]. Higher levels of collaboration in a firm's supply chain can lead to sharing of knowledge, enhance knowledge creation, and increase innovation spillovers from the supplier and innovation activities in general [52, 53]. Several firms are creating dense supply networks that foster collaboration to build the capability to compete well in the marketplace, where this capability is derived from the sharing of information and knowledge among their network of suppliers and customers [54, 55]. Analysis of a firm's supply network behavior moves beyond a linear, dyadic approach to consider the wider network of interactions that exist between suppliers, and it is this interplay between all members that can increase a firm's social capital and in turn significantly impact a their innovative output [8, 10].

Certain relationships in a firm's supply network—both direct and indirect—may be more suited to foster innovation; the direct behavior of a firm's partners and indirect behavior of others within the wider network both affect the firm's innovative output. Toyota, for example, established a series of supplier sub-networks to help facilitate the creation of strong ties and knowledge sharing among suppliers. While Toyota had to make early investments in subsidizing network activities, their return on these investments came through the establishment of highly interconnected, strong tie supply networks allowing greater diffusion of both explicit and tacit knowledge. Hence, one benefit from having highly interconnected supply networks is greater opportunity for firms to learn from the supply network and greater access to more leading-edge knowledge [8]. Second, in addition to the potential knowledge gains, higher supply network interconnectedness can also help decrease transaction costs [56]. Both of these benefits link back to a firm's structural capital, where opportunities are derived from the structure of a firm's direct partner supply network. Third, apart from benefits due to increased connectivity among supply chain partners, dense clustering in alliance networks has been linked to richer collaboration, resource pooling, and problem solving due to factors such as increased trust within structurally embedded, dense cliques [49, 57]. This increase in trust links back to a firm's relational capital, where this dimension of social capital rises from the dense clustering and forming of strong tie supply networks. Lastly, a focal firm operating in a densely connected supply network can also benefit from greater access to information that is more readily available and timely to the firm [34]. The series of redundant ties—where a focal firm has multiple indirect accesses to the same

partner through more than one direct relationship—can also help the firm to validate the reliability of information that is exchanged. As in the case of knowledge-access opportunities, these information-access opportunities are based on a firm's buildup of structural capital. In sum, a significant amount of the increased access to both knowledge and information described above can be attributed to the structural and relational social capital the firm leverages from its wider supply network [33].

The illustrations in Fig. 2 demonstrate the innovation-based benefits in establishing dense supply networks. These illustrations provide a comparison of two companies with very different supply network structures, but with similar overall supply network size. The lighter lines indicate a focal firm's direct connections, while the darker lines reflect the connections among that focal firm's partners. The focal firm is indicated by the biggest node in the graph. Also, the illustrations include the level of efficiency and the average number of granted patents from 2007 to 2009 for each focal firm. Schneider Electric has a direct supply network characterized by low density and hence a high level of efficiency. Conversely, Micron Technology has a very dense direct supply network with the multitude of ties offering several ports of access to knowledge, resources, and information.

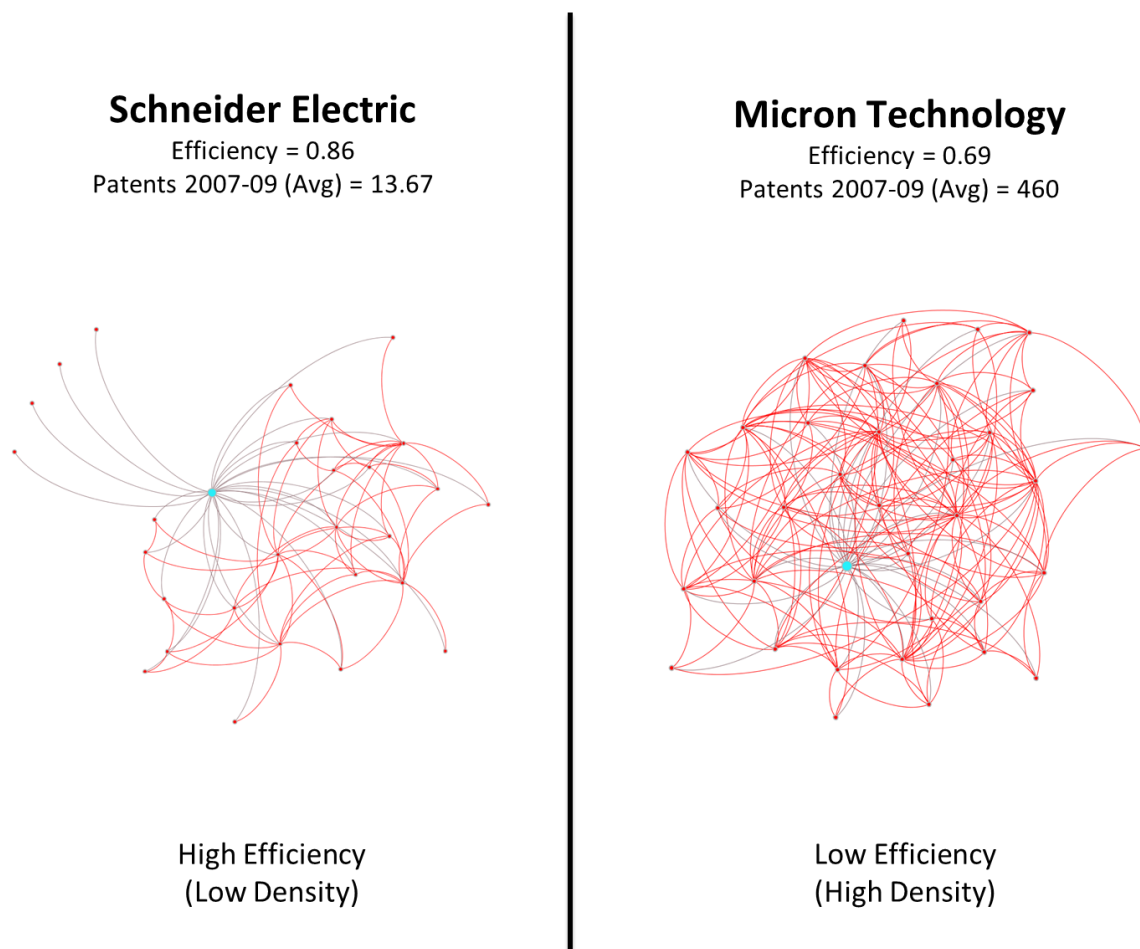


FIGURE 2.
Comparison of Electronic Firms with High and Low Efficiency Levels

We agree with the aforementioned studies that knowledge- and information-access opportunities are derived from densely connected networks. In terms of social network theory, a large number of between-partner ties would translate to a highly dense supply network. A greater number of ties shared between a firm's partners would signify greater facilitation of collaboration and knowledge transfer through the focal firm's supply network. These arguments lead to the following hypothesis:

Hypothesis 1: There is a positive relationship between the interconnectedness of a firm's supply network partners and its innovative output.

Supply Network Reachability

A firm's structural position in its immediate network can provide advantages or constraints that may affect the value of its structural dimension of social capital (Koka and Prescott, 2008; Burt, 2010). Certain firms may be able to access and transmit information across the supply network faster because of their unique structural position within the network. This structural position is based on a firm's compendium of direct and indirect ties, where firms who are able to reach a large number of members through a fewer number of intermediate relationships are well-positioned to obtain information quickly and with reduced risk of information distortion [49]. Firms who have this positional advantage in the supply network are referred to as central firms [12]. While prior studies have shown several efficiency benefits that derive from information access and transmission among supply chain members—such as reduced supply chain costs, shorter lead times and smaller batch sizes [58], lower inventory holding and shortage costs [59], and reduced stockouts [60]—, there are also many benefits which lead to an increase in a firm's innovative output. Prior research in information technology (IT) has shown that a firm's ability to access and transmit information is enhanced by its IT investments and its interactions with suppliers and customers. A firm can leverage its IT capability and its supply-based relationships to acquire and internalize quality data to build its analytical capability for knowledge discovery, enhance its realized capacity for transforming and exploiting knowledge, and solicit supplier and customer input and feedback during its innovation processes [61, 62].

Apart from the information-related benefits found in supply-based relationships, previous literature on interfirm alliances has also shown potential for firms to leverage their alliance ties to improve the speed of information, thereby increasing innovative output in several ways [48, 57]. One way is by enriching their own knowledge base from collaborative efforts, as opposed to lower knowledge acquisition due to reliance on equivalent but independent research and development (R&D) investments. Another way is by using collaboration to combine complementary skills from different firms, enabling the focal firm to benefit from economies of specialization sans investment burdens for internal development. Apart from direct network ties, indirect ties often act as information conduits or channels allowing access to knowledge spillovers, as firms transmit the knowledge and experience from each of their direct ties to their interaction with the focal firm, and vice versa [57, 63]. Also, indirect ties have the potential to serve both as an information-gathering and -processing devices, providing the focal firm with insight into technological developments, successes, and failures of several simultaneous research endeavors.

Firms who are in favorable structural positions based on their direct and indirect ties have the advantage of opportunity to obtain novel sources of information or, in the case of R&D technology-sharing, to develop products sooner than others [64]. This information-based advantage becomes more critical in the context of fast-moving industries, such as the electronics industry. Industries of this type are characterized by uncertain demand, low product life cycles, and highly innovative products [65]. We use illustrations to demonstrate the change in innovation output based on a firm's compendium of direct and indirect ties within the supply network. These illustrations in Fig. 3 provide a comparison of two companies with very different structural positions within the supply network. In this figure, the darker lines reflect the connections shared among that focal firm's partners, and the focal firm is indicated by the biggest node in the graph. While in Fig. 2 we focused on the relationships within and between the focal firm's direct supply network partners, here we also highlight the wider supply network that a focal firm has access to via its indirect connections. Avery Dennison has a relatively low level of reachability to other members in the supply network, compared with Sandisk who possesses a relatively high level of supply network reachability.

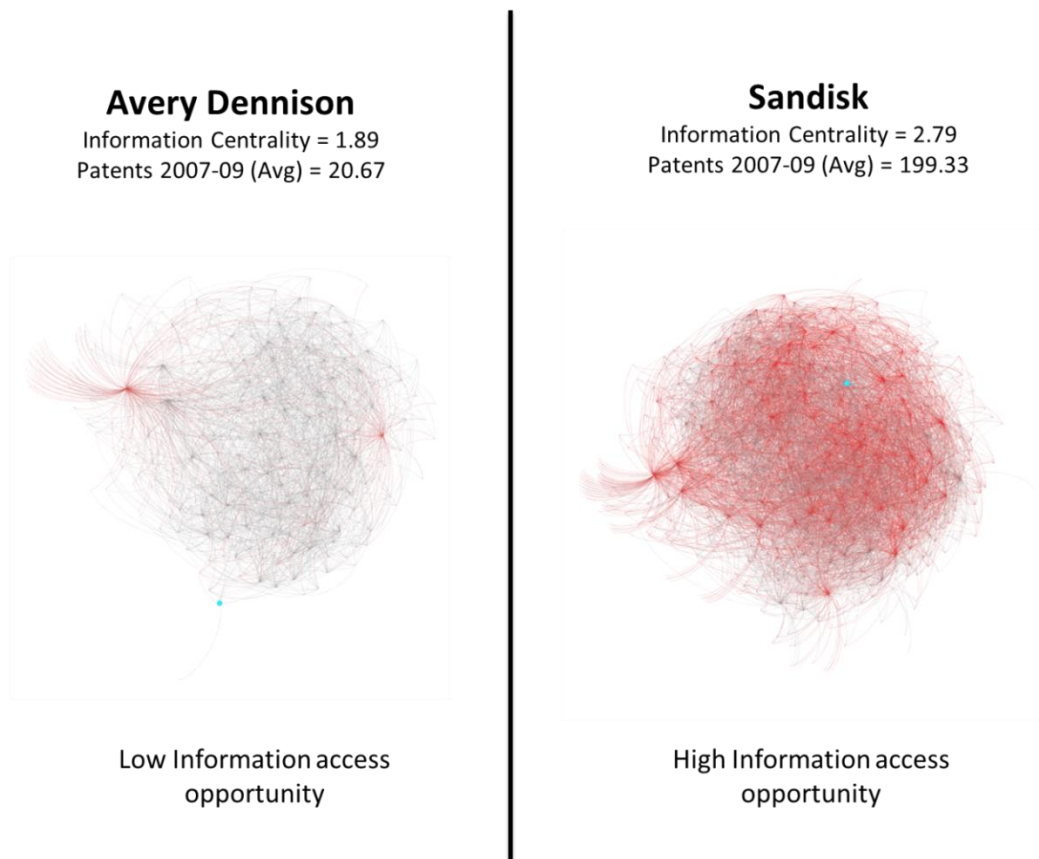


FIGURE 3.
Comparison of Electronic Firms with High and Low Information Centrality Levels

Viewing direct and indirect ties together, Ahuja [57] shows that a higher number of direct ties reduces the impact of indirect ties, signifying that direct ties moderate the impact of indirect ties on a firm's innovative output. The motivation here is that a focal firm with several direct ties is

already well-informed (thanks to the knowledge transmitted from its direct ties) and thus may only benefit marginally from knowledge flows through its indirect ties. Also, having an abundance of direct ties may hinder a focal firm from absorbing new information or responding to it as flexibly as firms with few direct ties. Take the series of buyer-supplier relationships, for example. Excessive interactions with the same suppliers puts a strain on the buyer's ability to search for other novel sources of information and capabilities available from other supply chain members, due to limitations in the firm's information processing capacity [15, 66]. Hence, we argue that the combination of direct and indirect ties that allows a firm wider reach and access in the network will enhance their potential to receive knowledge spillovers faster than others, which increases the likelihood of innovative output.

Hypothesis 2: There is a positive relationship between the level of reachability a firm has in the supply network and its innovative output.

Supply Network Partner Innovativeness

The emerging paradigm of open innovation is anchored in the idea that a significant amount of innovation is derived outside a firm's internal research development endeavors and greater, often novel learning is leveraged from outside sources [67]. As emphasized throughout this study, a firm's supply network partners are outside sources that have become a significant catalyst to increased innovation. While we have stressed the importance of (i) *how* a firm's supply network is structured and (ii) *how* the firm is structurally positioned in the overall network, *who* the firm is connected to is also an important factor that impacts innovation. Firms are recognizing the advantage in focusing on a supplier's ability to innovate and to act beyond mere parts providers [68], and this increasing recognition can be seen across several industries, such as automotive [69] and consumer goods [70]. When deciding supplier and customer value, a focal firm should consider each potential partner's level of innovativeness, as this level can determine the magnitude of available knowledge that can be leveraged and spill over to a firm and help with a firm's future innovation-based activities. The notion that supplier innovativeness can lead to useful learning by the buying firm has been conceptualized in Azadegan and Dooley [71]. Specific operational-based performance benefits have also received attention in supply chain literature. Innovative activities of suppliers have been linked to sustained operational functionality and reduced costs [23]. Azadegan and Dooley [22, 68] used an empirical survey to examine the impact of supplier innovativeness on various operations-based performance measures. However, as noted by the study authors, some limitations were that the manufacturer (not the supplier) was surveyed to report on each supplier's levels of innovativeness and manufacturers were from industry sectors with below average levels of innovation. Nonetheless, they shed significant light on supplier innovativeness as a catalyst that adds considerable value to the buying firm.

We argue that a supply chain partner's level of innovativeness not only helps in terms of operational performance, but can also enhance a firm's potential to receive knowledge spillovers and newer ways to recombine knowledge, problems, and solutions. Thus, we conjecture that the existence and level of external knowledge available to a focal firm through its supplier and customer base impacts the firm's innovative output. However, the extent to which the firm is able to absorb this external knowledge is also dependent upon a firm's absorptive capacity, which is the ability of a firm to understand and deploy knowledge obtained from other firms [26,

72]. An firm's absorptive capacity increases its ability to adapt a supplier's innovation and expertise to its own needs [73] as well as its efficacy to assimilate and apply this external knowledge [74]. Based on this, we speculate that absorptive capacity of a firm creates an upper bound on its ability to leverage the external knowledge available through its supply network. Once this upper bound is reached, the firm risks stifling the innovative capabilities that it currently has by using resources in attempt to extract more innovation from external sources that it is actually capable of. While this upper bound may increase through greater investments in internal R&D capabilities [72], greater internal investments work against the open innovation strategy to invest more in external relationships. Hence, we expect a negative quadratic relationship between supply network partner innovativeness and a firm's innovative output.

Hypothesis 3: There is an inverted-U relationship between the level of innovativeness of supply chain partners and a firm's innovative output.

Moderating Role of Supply Network Interconnectedness

Firm's with more densely connected supply networks will have greater opportunity to access and transmit information, as this increases the likelihood that they will be able to reach any given supply chain member through fewer intermediate relationships. Thus, we expect that there should be an interaction effect that occurs between a firm's level of supply network interconnectedness and its ability to reach any given member in the supply chain through a fewer number of intermediate relationships. A lack of interconnectedness among a focal firm's supply chain partners will result in a series of supplier sparse sub-networks networks that are broken into fragments of disconnected firms, forming *structural holes*. A supply network has several structural holes if connections among partnering firms are themselves unconnected or only loosely connected to other clusters of connected firms, resulting in a very fragmented network.

Structural holes in a focal firm's supply network may lead to lower levels of trust and a higher threat of opportunistic behavior, and hence lower resource-sharing benefits, potentially hindering innovation gains from relationships established. However, structural holes in the overall network of a given industry can be exploited by boundary-spanning firms with more opportunity to increase their level of access to diverse information across the wider supply network. Firms who span these structural holes often occupy positions of considerable influence [75]. This point on structural holes also emphasizes the difference between the level of interconnectedness in a firm's supply network and the firm's structural position, the latter bearing greater influence on their ability (or inability) to span structural holes.

Schilling [49] empirically supported the argument that the combination of clustering and reach was associated with significantly higher firm innovation. The constructs of (1) clustering and (2) reach are highly correlated with our use of the constructs of (1) supply network interconnectedness and (2) supply network reachability. In the context of fast-moving industries, which is characteristic of our industry of study (the electronics industry), we posit that firms who maintain dense supply networks (i.e. highly interconnected supply networks) while spanning structural holes (through increased supply network reachability) will experience a greater increase in innovation than firms with who span structural holes but across sparser supply networks. Based on the discussions so far, we hypothesize the following:

Hypothesis 4: The positive relationship between a firm's supply network reachability and their innovative output will be larger among firms with densely connected supply networks.

DATA AND METHODS

Research Settings in the Electronics Industry

To test our hypothesis, we constructed a large database of firms who served as customers and/or suppliers in the electronics industry during periods 2005 to 2008. We chose the firm as our unit of analysis and the high velocity electronics industry as our research setting. The choice of the electronics industry was particularly important for this study for many reasons. First, the electronics industry is a great source for finding examples of dispersed innovation networks resulting from the interactions between the industry's customers and suppliers. The industry has transitioned from being dominated by large vertically integrated companies—such as IBM, HP, Toshiba and Fujitsu—into an industry where companies have formed global production networks and rely heavily on outside suppliers for integration of knowledge and technology [76]. Second, knowledge creation is central to the pursuit of competitive advantage in industries designated as high-technology [49], with the electronics industry clearly falling under this designation. High-technology industries such as the electronics industry are characterized with high market unpredictability, shorter product life cycles, and globalization [77]. This environment puts greater pressure on firms to leverage the knowledge and technology of their partners to continually produce product and process innovations that add customer value. Since we are interested in the knowledge flow that arises from supplier alliances, the electronics industry is a fitting research setting for examining knowledge creation among customers and suppliers. Third, because we examine patenting activity to detect a firm's innovative output, we needed to ensure that the industry of choice is characteristic of firms who actively patent their inventions. Prior research supports our choice by showing that firms in the semiconductor, computer, and communications equipment sectors—all prevalent sectors in our industry sample—actively patent their inventions [78].

Global Electronics Supply Network

Our study is based on a sample of leading firms in the electronics industry. The primary sources of our data collection were: the Electronics Business 300 (EB 300) listings, the Connexiti database, and the Thomson Reuters SDC Platinum Joint Ventures/Alliances database. Our use of archival data in measuring characteristics of supply networks avoids the common method bias commonly associated with survey data.

First, we identified all unique firms listed in the EB 300 dataset from 2005 to 2009. The EB 300 dataset is an annual listing top global 300 electronics firms ranked by electronics revenue and was created by Electronics Design, Strategy, and News (EDN). The reported revenue is calculated using segmentation information and Reed Research estimates on revenue from the sale, service, license or rental of electronics and computer equipment, software, or components. The EB 300 dataset has been used in other electronics industry studies [e.g. 79]. Next, we performed another check for quality and consistency by comparing our data set with EB 300

firms identified by Shin [79] for years 2000 to 2005. Any unique EB 300 firm identified by this study time period but not in ours was also included into our sample. Our initial dataset included 582 unique firms. Since we focus on lead companies, contract and original design (ODM) manufacturers, and component suppliers in the electronics industry, we limited inclusion to these types of firms. Thus, the selection process based on our focus resulted in a final sample of 151 leading firms in the electronics industry.

Second, we identified the supplier and customer relationships for these 151 leading firms using the Connexiti database. Connexiti is a comprehensive supply chain intelligence database consisting of supply and customer relationships for nearly 20,000 global companies. The Connexiti database contains information on suppliers, customers, competitors, and partners. This information is retrieved from SEC filings, company press releases, website updates, analyst reports, and earning transcripts. Previous research has used Connexiti to study alliance networks in the high-tech industry [e.g. 80]. Consistent with the years of focus for our EB 300 data set, we examined all active supplier and customer relationships from years 2005 to 2008, with relationship data spanning up to early 2009. By combining the list of suppliers with set of 151 leading firms, our dataset consisted of 911 focal firms having 7,311 supplier and customer relationships among all firms.

Third, we cross-validated and augmented our sample dataset with information from the SDC database. The SDC database is a commonly used data source that includes data on strategic alliances as well as supply, R&D, marketing, licensing and manufacturing agreements. SDC data has been used in a number of empirical studies on strategic alliances and interorganizational networks [e.g. 49, 81]. For our data collection process, we focused on publicly reported contractual alliance agreements via Connexiti and SDC databases. We acknowledge that there exists a series of informal collaborative arrangements among firms in our sample, which spur knowledge transfer among firms. However, we choose to rely on often more objective, secondary data to drive our results. Also, many of these informal relationships will manifest themselves through observable formal agreements [50] that we observe with our data collection.

The next step was to construct a supply network reflective of the supplier and customer relationships as of the end of 2008. Since supplier alliances typically last for longer than one year, constructing our supply network based solely on relationships announced in the focal year risks biasing the connectivity of the extended networks beyond a focal firm's direct partners, and potentially the number of direct partners themselves. Thus, resorting to alliances formed only in 2008 may fail to account for the pre-existing alliance relationships that have been maintained through 2008. We decided to survey several research studies to get a better sense of the mean duration stated for supply chain relationships. Our search revealed a wide spectrum of relationship durations between two dyads in studies, in particular for supply chain studies with a significant representation of the electronics industry. These studies revealed supplier and customer relationships to last an average of 12.42 [43], 2.06/2.70 [56], and 12 years [82]. Researchers studying strategic alliance networks have supported the use of three-year windows as a more conservative approach to mitigate potential bias in the network structure [e.g. 49]. In consideration of all of these factors, we took a conservative approach by including the all active supplier and customer relationships for the past three years leading up to 2009. The data on the supply network was used to operationalize each of the theoretical constructs used in our

hypothesis that we link to a firm's innovative output. Before describing our explanatory measures driving innovation, we first explain how we capture a firm's innovative output.

Dependent Variable: Innovative Output

Following suit with several other researchers, we use the number of patent grants as an indicator of a firm's innovative output [e.g. 74, 83, 84]. Patents serve as useful measures of novel, non-obvious inventions that reflect advancements over existing technology and are externally validated through the patent examination process. Hauser et al. [85] argue that protecting one's lead in technological evolution, and hence achieving competitive advantage, is done by securing patents. Recent studies have also shown support for the assertion that firms who possess a larger number of patent inventions are more likely to transform their inventions into a larger number of new products and services introduced to the market [62]. We represent the innovative output of a firm by the average number of patent applications granted in years 2007 to 2009.

We include a patent in a given year based on its date of application. Using a granted patent's application date allows us to have a closer indication of when the invention occurred, as an invention is estimated to have occurred about three months prior to the patent application date [86]. Inventions can then be used to trace back a firm's knowledge creation activity. The underlying logic is that inventions serve as a way to instantiate knowledge creation [87] and the accumulation of knowledge engrained in inventions is used to facilitate a firm's processes that generate novel actions from a given set of resources [88].

We acknowledge that there are concerns associated with the use of patent count data that merit discussion. The first concern is the potential right censoring bias when using patent applications granted, as the majority of patent applications are either granted or abandoned within two to three years of application. In fact, over the past ten years, we verified that the average time from the patent application filing date to the date of disposition (granted or abandoned) has been 2.5 years [89]. In order to mitigate any right censoring bias, our time series consists of all patent applications granted up until March 2012.

The second concern is the argument that citation-weighted patent counts better reflect an innovation's quality than patent counts alone. Prior empirical research, however, has established patent count data as reliable in itself by showing the high correlation between patent count and citation-weighted patent measures. In fact, correlations for the two measures were found to be 0.925 ($p < 0.001$) in the electronics and communications industry [51], 0.973 ($p < 0.001$) in the computers and office machinery industry [51], and greater than 0.80 ($p < 0.001$) in the semiconductor industry [48], rendering this assertion more generalizable. Hence, this provides support for our use of patent counts to reliably proxy the same underlying theoretical construct as citation-weighted patent counts. Further, patent counts have been shown to be positively correlated with invention counts [90], new product introductions [91], and technical capabilities [92], and have been regarded as valid and robust indicators of knowledge creation [93]. Lastly, the measure of citation-weighted patent counts brings about its own imperfections. Previous studies [See 94] point out the following sequential issues: (1) it is common for patent examiners to add citations to patent applications, suggesting that applicant firms are not necessarily aware of all cited patents, (2) these third-party citations often generate noise in the measurement of

patent-based variables, (3) as a result, the noise generated increases standard errors in the estimators and reduces the likelihood of finding statistically significant effects.

We retrieved the patent data from the United States Patent and Trademark Office (USPTO) & Classification and Search Support Information System (CASSIS) Database. We obtained data on patents issued to each company in our sample and cleaned and organized the data on an annual basis. The average firm in our sample was granted approximately thirty-three patents per year.

Independent Variables

We operationalize our supply network constructs by the measurement of two structural characteristics: (1) *network efficiency* to measure the interconnectedness a firm's direct partner supply network and (2) *information centrality* used to measure supply network reachability. Consideration of a supply network's structural characteristics give rise to constructive quantitative assessments of a particular firm's level of power, influence, and embeddedness in the supply network [7]. To calculate these measures, we first construct an undirected binary adjacency matrix reflecting the 7,311 supplier and customer relationships among all firms in our sample. Within our binary adjacency matrix, each cell entry is marked as 1 if there is any relationship between two companies and 0 otherwise. We chose to represent multiple relationships between the same pair of firms as one link in our network for two reasons. First, our primary focus is whether a relationship between two companies exists and not with multiplex relationships [see 95]. Second, collaborative relationships are typically considered to be bidirectional [96]. For example, in the electronics industry, several products require the integration of sophisticated components that result in ongoing communication and interaction between customers and suppliers about process and design phases for assembling and testing these products.

We used UCINET 6.365, a social network analysis package [97], to compute the two independent variable measures. The measures are based on the use of social network analysis, a distinctive methodology grounded in principles from matrix algebra and graph theory [98]. A growing number of supply chain management studies have adopted concepts and tools founded in social network theory [e.g. 5, 12, 14]. We describe both measures to follow. We also provide an example calculation for a simplified network in the appendix. For even further clarification on how these measures are calculated, readers can refer to [99] and [34]. Lastly, readers can also revert back to Fig. 2 and 3 comparing the measures of four companies in our sample.

We account for the level of *supply network interconnectedness* by using the following equation for *network efficiency* from Burt [34]:

$$Effic_i = \left[\sum_j \left[1 - \sum_q p_{iq} m_{jq} \right] \right] / n_i \quad (1)$$

where p_{iq} is the proportion of focal firm i's ties invested in the relationship with q, m_{jq} is the marginal strength of the tie between members j and q (who are both directly connected to i) and n_i is the total number of direct partners of focal firm i. Since our supply network representations are binary, binary data, the values of m_{jq} are set to 1 if a tie is present between members j and q and zero otherwise. Based on this representation, greater network efficiency (a larger number)

would correspond to a lower level of *supply network interconnectedness* and vice versa. Thus, since this measure works in the opposite direction as our hypothesized construct, *network efficiency* score should correspond to lower innovation output and should be negatively associated with innovation output. As a note, authors studying real-world strategic alliance networks have captured similar effects using the clustering coefficient measure from UCINET [e.g. 49]. In our study, the measure of clustering coefficient was highly correlated with the measure of network efficiency (-0.95). For the sake of comparison and a more complete analytical approach, we re-ran our model substituting clustering coefficient for network efficiency. This substitution revealed very structurally similar results that agree with the findings from our modeling choice.

We operationalize *supply network reachability* by using *information centrality* [99]. *Information centrality* is measured by using the harmonic mean length of paths ending at a vertex i , which is smaller if i has many short paths connecting it to other vertices:

$$IC_i = \frac{n}{nc_{ii} + (T - 2R)} - \frac{1}{c_{ii} + (T - 2R)/n} \quad (2)$$

where

$$C = (c_{ij}) = B^{-1}, T = \sum_{i=1}^n c_{ii}, R = \sum_{j=1}^n c_{ij} \quad (3)$$

The values which make up c_{ii} , which are the diagonal values in the inverted matrix B^{-1} , are calculated as the number of direct ties firm i has, plus 1. The values for c_{ij} 's are based simply on whether there exist a tie between firm i and firm j . If no tie exists, the value is 1. Otherwise, if a tie between the two does exist, the value is 0. The index has a minimum value of 0, but not maximum value. The variable n corresponds to the number of firms in the network of interest. In our sample, the values for information centrality ranged from a minimum of 0.69 to a maximum of 2.80.

We operationalize *supply chain partner innovativeness* by measuring what's referred to as the technological capital of a firm. Technological capital is one way to measure a firm's level of technological competence [100] and has been calculated as a firm's patenting activity in the previous five years to assess the technological impact in previous studies looking at high-tech industries [e.g. 57, 101]. Previous scholars point out how a firm's current technological stance is often dependent on its previous level of technological know-how, due to the cumulative nature of technology. Lastly, a firm's level of technological capital can be seen to represent the depth of a firm's technological resources and absorptive capacity [72, 102].

Control Variables

In our model, we control for the following variables: firm size, industry affiliation, regional affiliation, R&D intensity, and a firm's technical capital. Financial data was retrieved from the COMPUSTAT database and cross-examined using the Mergent Online database. *Firm size* has been shown to influence its internal innovation processes and can have both negative and positive effects on its innovation [103]. We controlled for firm size using the natural log of sales. We controlled for industry effects by incorporating the three-digit North American Industry Classification System (NAICS) code for each firm. We also controlled for region by

coding indicator dummies for North America, Asia, and Europe (with North America as the omitted variable).

Research has suggested that a firm's absorptive capacity is largely a function of its investment in R&D and its level of prior related knowledge [72]. Thus, we included *R&D intensity* as it has been commonly linked to innovation and can contribute to a firm's ability to absorb outside knowledge [74]. We calculated *R&D intensity* as the R&D expenditures measured as percentage of total sales. We controlled for firm profitability by including *return on assets (ROA)*, calculated as the net income over total assets. We also controlled for firm liquidity by including each firm's *current ratio*, calculated as the ratio of current assets to current liabilities.

Model Specification

We operationalize innovative output by using the number of granted patents as our dependent variable. This makes our dependent variable a count variable that takes on only non-negative integer values. Hence, a linear regression model would be inappropriate as it assumes the distribution of residuals to be homoscedastic, normally distributed. This could lead to coefficient estimates that are both biased and inconsistent [104]. Poisson and negative binomial regression are more appropriate models for count data. Because of the presence of overdispersion in our patent data, the strong assumption of Poisson regression that the mean and variance are equal does not hold. The negative binomial model accounts for overdispersion and helps avoid spuriously high levels of significance due to coefficients whose standard errors are underestimated [105]. By inspecting the likelihood ratio test, we found strong evidence for the negative binomial model as more appropriate than the Poisson model for our data ($p = 0.000$).

The negative binomial model has the following form [106]:

$$\mathcal{L} = \sum_{i=1}^n \left\{ y_i \ln \left(\frac{\alpha \exp(x_i' \beta)}{1 + \alpha \exp(x_i' \beta)} \right) - \frac{1}{\alpha} \ln(1 + \alpha \exp(x_i' \beta)) \right. \\ \left. + \ln \Gamma \left(y_i + \frac{1}{\alpha} \right) - \ln \Gamma(y_i + 1) - \ln \Gamma \left(\frac{1}{\alpha} \right) \right\} \quad (4)$$

The above equations for the model are expressed as log-likelihood functions, as is typical for a count model. In the above equations, y_i refers to the patent count, the x_i 's refer to each explanatory variable (*R&D intensity*, *ROA*, *current ratio*, *hierarchy*, *industry*, *regional affiliation*, *network efficiency*, *information centrality*, *network efficiency*information centrality*, and *supply network partner innovativeness*), α reflects the value of the heterogeneity or overdispersion parameter, and β represents the model coefficients.

In addition to proper model specification, we took several measures to help avoid any signs of multicollinearity in our model. First, we used the grand mean-centered values of both independent variables, which helps eliminate multicollinearity due to the inclusion of interaction terms. Second, we ensured that the variance inflation factor (VIF) scores for each predictor variable were below a value of 10, signifying that multicollinearity is not an issue in the given dataset (Neter et al., 1996). Each of the VIF scores for our dataset met this requirement (mean score of 1.62) after we mean-centered the three independent variables. We also had to employ strategies to ensure that the data accounted for other underlying issues brought upon by

influential observations in the data. An influential observation is found when removing that observation causes a substantial change in the estimate of coefficients. Hence, we calculated the Cook's D values [107] for each observation to find any observations with very large residuals or with an extreme value on any one of the predictor variables. We excluded any observations that lied above the conventional cut-off of $4/n-k-1$, where n is the sample size and k is the number of predictor variables in the model. This reduced our sample size from 489 to a final sample size of 425 firms. We ran all analyses in STATA Version 11.

RESULTS

To be included in the final analysis, a particular firm had to satisfy the following criteria: (1) the firm has patent data available for years 2002-2012, whether they had actually patented anything in a given year or not and (2) the firm has financial data on R&D expenses, sales, income, assets, and liabilities for the fiscal year 2006 and (3) there is no evidence of disproportionate influence on the regression model by adding data for a particular firm. Hence, any firms who had missing information in criteria (1) and (2), or whose inclusion distorted the regression model affecting criteria (3) (checked by Cook's D as described earlier), were dropped from the analysis. As with many industry studies, finding key financial information for private firms is often not possible and thus reduces the sample. The descriptive statistics and simple correlations are presented in Table 1. These results reflect the expected overdispersion and evidence of excess zeros (25.12% of firms) in our dependent variable measure.

TABLE 1.
Descriptive Statistics and Correlations

	Variable	Mean	Std. Dev.	Min	Max	1	2	3	4	5	6	7	8
1	Patents	32.76	106.30	0.00	1173.33	1							
2	R&D Intensity	0.26	1.28	0.00	24.06	-0.04	1						
3	ROA	-0.06	0.45	-5.61	0.45	0.09	-0.29*	1					
4	Current Ratio	0.38	0.32	0.00	2.68	0.01	-0.05	0.12*	1				
5	Hierarchy	0.17	0.29	0.00	1.00	-0.07	0.06	-0.22*	-0.12*	1			
6	Information ^b	0.84	0.14	0.33	1.00	-0.09	-0.07	-0.15*	-0.02	0.41*	1		
7	Efficiency ^b	1.97	0.64	0.69	2.80	0.22*	-0.11*	0.23*	0.11*	-0.57*	-0.35*	1	
8	Supply Network Partner Innovativeness ^b	22.91	35.37	0.00	272.22	0.18*	-0.04	0.1*	0.00	-0.13*	-0.05	0.58*	1

Notes: N = 425 observations. All correlations with magnitude > |0.095| are significant at $p < 0.05$ level, as signified by an *. Variables were grand mean-centered.

TABLE 2.
Negative Binomial Regression Model

	Dependent variable: Patents			
Variables:	Model 1	Model 2	Model 3	Model 4
R&D Intensity	1.33*** (0.36)	0.70+ (0.36)	0.62+ (0.36)	0.57 (0.36)
ROA	4.00*** (0.68)	2.63*** (0.66)	2.44*** (0.65)	2.35*** (0.64)
Current Ratio	-0.10 (0.46)	0.62 (0.39)	0.64+ (0.39)	0.65+ (0.39)
Hierarchy	-0.66 (0.46)	0.92* (0.45)	0.60 (0.47)	0.12 (0.52)
Efficiency ^b		-1.91* (0.82)	-1.81* (0.82)	-2.92** (0.94)
Information ^b		0.83*** (0.25)	0.46+ (0.27)	0.54* (0.27)
SN Partner Innovativeness ^b		0.01** (0.00)	0.03*** (0.01)	0.03*** (0.01)
(SN Partner Innovativeness) ²			-0.00** (0.00)	-0.00** (0.00)
Information*Efficiency				-3.80* (1.66)
Constant	3.77*** (0.64)	2.55*** (0.61)	2.56*** (0.60)	2.60*** (0.60)
Industry Dummies	Yes	Yes	Yes	Yes
Regional Dummies	Yes	Yes	Yes	Yes
Log Likelihood	-1423.92	-1414.53	-1409.81	-1407.10
Δ Log Likelihood	-	9.39	4.72	2.71
Vuong	3.30 (p<0.001)	3.34 (p<0.001)	3.26 (p<0.001)	3.22 (p<0.001)
N	425	425	425	425

Notes: Standard errors in parentheses; *** p<0.001, ** p<0.01, * p<0.05, + p<0.10

^b Variables were grand mean-centered.

The results of the negative binomial regression are presented in Table 2. For the sake of brevity, industry and regional effects are not included in the results table. Instead, we include corresponding rows indicating whether or not industry and regional effects were estimated in each model. The effects are introduced sequentially to help ensure model stability and to make sure that any significant effect is robust to the inclusion of other effects. Thus, Model 1 of Table 2 includes only the control variables. ROA is the only control that remains significant across all models and is shown to positively impact the level of innovative output. Model 2 includes the direct effect of supply *network efficiency*, firm *information centrality*, and supply *network partner innovativeness*. Consistent with Hypothesis 1, Model 2 reveals *network efficiency* has a negative and significant effect on innovative output. Model 2 results also suggest that the degree of innovative output increased with an increase in *information centrality*, in support of Hypothesis 2. Lastly, Model 2 reveals a positive and significant association between supply

network *partner innovativeness* and firm innovation. The model is also a significant improvement over Model 1 (Δ likelihood ratio: 9.39; df: 1; $p < 0.001$). As a note, we also tested the main effects each of the three explanatory variables separately (*network efficiency*, *information centrality*, and *supply network partner innovativeness*) and the significance and direction was consistent with our results in Model 2. Model 3 includes supply network *partner innovativeness* and its squared term. The results indicate that this construct is significant and in the (inverted U) shape expected in Hypothesis 3. We also tested the effects of *supply network partner innovativeness* and its squared term without the main effects from *network efficiency* and *information centrality*; the results held the same as found in Model 3. Again, this model shows a significant improvement over all preceding models, in particular Model 2 (Δ likelihood ratio: 4.72; df: 1; $p < 0.001$). Lastly, Model 4—which incorporates the interaction term of a firm’s *supply network efficiency* with its *information centrality*—is an improvement upon all previous models (e.g. compared with Model 4, Δ likelihood ratio: 2.71; df: 1; $p < 0.001$) and verifies that our previous three hypothesized effects are robust to the inclusion of all model variables. The interaction term of a firm’s *supply network efficiency* with its *information centrality* is negative and statistically significant, giving strong support for Hypothesis 4. Further interpretation of this moderating effect can be enriched by using interaction plots of the two variables using the log-linear form of the model.

Fig. 4 shows the plot of the interaction between a firm’s *information centrality* with its level of efficiency. The “low efficiency” line relates to our moderating effect and depicts the slope of the effect of *information centrality* on patents when the value of efficiency is set to one standard deviation below its (mean-centered) mean. In contrast, the “high efficiency” line reflects the slope of the effect of *information centrality* on patents when the value of efficiency is set to one standard deviation above its (mean-centered) mean. The end points of both lines are calculated at one standard deviation below and above the mean of *information centrality*.

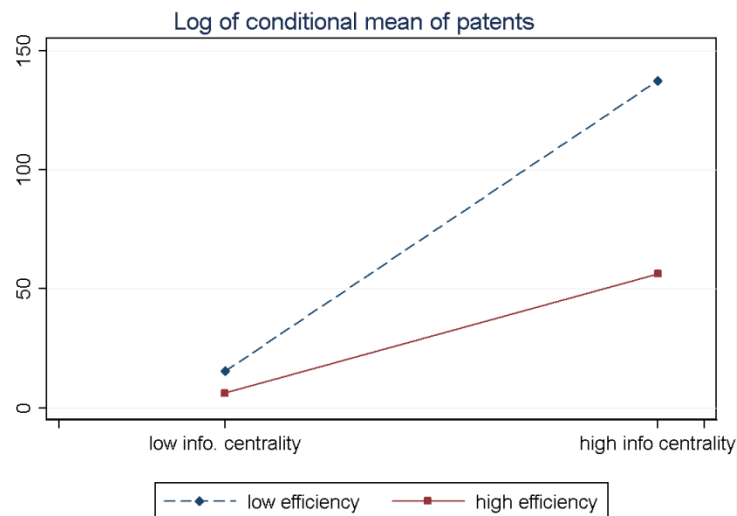
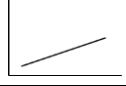
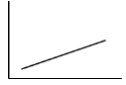
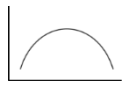



FIGURE 4.
Effect of the Firm’s Network Efficiency on the Impact of its Information Centrality

TABLE 3.
Summary of Findings

Hyp.	Factor(s)	Impact on Innovation	Support?
1	Supply Network Interconnectedness		Yes
2	Supply Network Reachability		Yes
3	Supply Network Partner Innovativeness		Yes
4	Supply Network Interconnectedness * Supply Network Reachability		Yes

DISCUSSION

Table 3 summarizes our findings. Throughout this study, we have emphasized a firm's supply network partners as outside sources who can become a significant catalyst to increased innovation. We have stressed the importance of how a firm's supply network is structured, how the firm is structurally positioned in the overall network, and who the firm is connected to as important factors that impact innovation. Scholars have argued that future research on social capital in supply chains would benefit from a deeper structural analysis accounting for the embedded nature of buyer-supplier dyads [5, 15]. We contribute to theory on supply chains and innovation by analyzing the social capital benefits from each supply network partner based on its internal capabilities (e.g. innovativeness) and also indirectly through each partner's extended network of relationships. This study has implications for this growing research stream as well as for executives managing supply chains.

Theoretical Implications

A key objective of this research was to examine and empirically test the impact of some important structural characteristics of supply networks and partner innovativeness on a firm's innovation output. We investigated the relationships and impact of supply network interconnectedness, supply network accessibility, and supply network partner innovativeness on a firm's innovation output. We found empirical evidence of the importance of each of these key structural network attributes as mechanisms driving a firm's innovation capability. There has been a growing recognition in the literature of leveraging supply networks as a superior source of innovation and building social capital [5, 108]. The findings in this study contribute to this stream of research.

The findings for the main effects of supply network interconnectedness on innovation output are inconclusive, indicating lack of support for Hypothesis 1. Our main premise was that this

interconnectedness helps foster collaborative initiatives that provide access to knowledge, resources, and information from other members in the supply network. We expected that these shared relationships would help increase the likelihood of collaboration among a firm's direct partners as the partners may realize the shared fate from their interdependency with each other and thus be more willing to cooperate. Moreover, we expected that these shared relationships would also allow the focal firm greater ports of access to obtain these benefits. However, lack of support for its positive or negative relationship suggests that supply network interconnectedness, in isolation, may not be a driver of a firm's innovation capability. While the forming of densely connected supply networks may facilitate collaboration to help induce cooperation, knowledge sharing, and information reliability [109], it can also restrict the novelty of information and new learning opportunities to take advantage of. This is especially true when competitive environment changes occur in the primary industry in which a firm operates [110]. While our theory draws on prior research investigating the positive and negative consequences of having a lowly or highly interconnected supply network, it appears that there are other mechanisms at play that are more important in driving a firm's innovation capability. Instead, the impact of having several shared relationships among partners may manifest itself indirectly by moderating the effect of other mechanisms on innovation output, such as supply network accessibility.

We show that the level of accessibility that a firm has into the supply network – as derived from its structural position – has a direct benefit on its innovation output, providing support for Hypothesis 2. This is in agreement with the literature saying that firms with high accessibility experience a greater quantity and diversity of information from the network in which they operate [49]. Greater accessibility from a firm's supply network can help foster greater opportunities to collaborate and help the focal firm reap the benefits of novel information flow that leads to higher innovation output. The results of this study also support for Hypothesis 4 by demonstrating the value of maintaining densely connected supply networks while simultaneously spanning structural holes via increased supply network accessibility to boost innovation output. This moves the consideration of supply network structure beyond direct partners and relationships between direct partners (local scale) to also consider the indirect relationships with other members of the wider supply network (global scale).

Our results confirm our predictions that supply network partner innovativeness positively influences firms' innovation output but with diminishing returns, in support of Hypothesis 3. This provides empirical support for the suggestion that firms experience tradeoffs as they approach their absorptive capacity levels which may reflect in diminished innovation capability [73]. Further, while we find a positive linear relationship between internal investments in R&D and innovation output, we also find R&D intensity to positively moderate the impact of supply network partner innovativeness. This result supports Hypothesis 5, and suggest that leveraging both internal investments in R&D as well as the innovativeness of supply network partners is a better approach than a singular focus on internal R&D investments for continual growth in innovation [71]. Thus, investing more in internal R&D, as a form of absorptive capacity, can be used to mitigate the diminishing effects of the innovativeness of a firm's supply network partners.

Managerial Implications

Our research findings also suggest the potential benefits of a firm strategy to manage their supply network with a particular focus on structural components. Our results show further support for previous literature stressing the importance of adopting a supply network perspective when identifying and evaluating supply network partners [3]. This would require firms to reconsider the value of their key supply network partners based on the social capital that exists directly and indirectly through each partner's extended network of relationships. The trend of firms building core competencies in-house but outsourcing non-core competencies has made them more dependent on the knowledge and expertise of its supply network partners to avoid sub-optimal solutions to problems, to innovate, and to adapt [111]. Managers should invest more in IT and interactions with its suppliers and customers to help recognize their dependence on other firms and focus their strategy on maximizing opportunities to access external knowledge [112] as well as solicit supplier and customer input and feedback during its innovation processes [61]. Adopting a supply network perspective and making these investments can help firms focus on customers and suppliers that provide the most value to their innovation capability, before going the next step in strengthening ties through initiatives such as sharing knowledge and technical advice with them, and providing and encouraging opportunities to work with other suppliers [41].

This renewed perspective of customer and supplier value can also apply to the manager's future selection and supply network reconfiguration strategy. Autry and Griffis [5] note the prospect of future research to investigate a firm's decision "to invest in competitive intelligence that can be used to optimize the structure of the supply chain by identifying the most attractive partnering opportunities." This sort of strategic approach suggests that a firm focus more on investments that promote structural changes (related to the supply network structure) rather than relational ones (related to direct investments in relationships with customers or suppliers). This approach could also result in more direct intervention of a buying firm to reconfigure its suppliers' external networks or communications structures [3]. In the context of our study, it would seem beneficial for supply chain executives—whose focus of building competitive advantage is through innovation leadership—to assess the level of redundancy among their partner supply networks and their overall supply network accessibility for the sake of influencing the lead time of information flow and increasing their ports of access for knowledge and information sharing.

Limitations and Directions for Future Research

We acknowledge that our research findings do pose some limitations. While we include a firm's R&D intensity and prior patenting success as a reflection of a firm's absorptive capacity, there may be other important factors capturing the firm's amount of experience and potential ability to absorb incoming external knowledge. Future research should delve further into other aspects that may affect a firm's ability to leverage its supply network for increased knowledge.

Our study emphasized the embeddedness of a firm and the interconnectedness of its partners, which inherently focuses on the structural dimension of social capital. We acknowledge that there are other dimensions of social capital that merit consideration. Several supply chain studies in have looked at social capital from three dimensions: structural, cognitive, and relational capital [33] The structural dimension of social capital refers to the overall pattern of connections

between partnering firms, mapping who a particular firm reaches and how they reach them. From this dimension, the network structure derived from a firm's series of ties determine, in part, opportunities and constraints to access valuable resources and information that would help them sustain a competitive advantage [34]. The cognitive dimension refers to those resources that help generate shared language and vocabulary and the sharing of collective narratives [33]. Lastly, the relational dimension of social capital refers to the degree of mutual respect, trust, and close interaction that exists between a firm and its partners [37, 38]. We did not incorporate the factor of relationship strength, reflecting the importance or value of each supply network link. For example, some suppliers may be providing very standard components with little value added whereas other suppliers may be providing a critical component that adds considerable market value. Also, firms may rely heavier on a certain customer based on the percentage of revenue they receive from that customer.

Lastly, the organizational learning literature distinguishes between the types of innovation based on the degree of new knowledge embedded in an innovation, resulting in a continuum of innovations that range from incremental to radical [20]. Incremental innovations emphasize the development of existing resources, knowledge, or abilities and are regarded as containing a low degree of new knowledge. Conversely, radical innovations emphasize the search and discovery of new resources, knowledge, or abilities and are regarded as containing a high degree of new knowledge [20, 21]. We do not distinguish between types of innovation in our study, but future studies may benefit from accounting for this.

CONCLUSION

Through our empirical analysis, we find further evidence supporting the argument that network structures and supply network relationships that form supply networks are critical components for identifying strategic imperatives in supply chain management [6, 12]. We contribute to research the body of literature on both supply chain management and innovation by highlighting how the level of supply network interconnectedness, supply network accessibility, and supply network partner innovativeness, can significantly improve upon a firm's level of innovation output.

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